Conservation of the endangered Green and Golden Bell Frog: what contribution has ecological research made since 1996?

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ABSTRACT

The status and conservation requirements of the Green and Golden Bell Frog *Litoria aurea* were the focus of immense scrutiny 12 years ago. In this paper I review what progress has occurred since then in understanding the ecology of this species because ecological research is of fundamental importance to the recovery of threatened species. Field surveys and collation of unpublished information have led to a very detailed understanding of the distribution of this species, including recognition that some populations have become extinct since 1996. Population studies involving the permanent tagging of individuals have revealed substantial variation in the size of populations but further research is needed to relate population size to viability.

Two major threatening processes (habitat loss and predation by exotic fish) were implicated in 1996 in the decline of the Green and Golden Bell Frog, though others were acknowledged. Provision of breeding habitat has been a key element of bell frog management since then but despite some success, there have been few general insights gained concerning its effectiveness to allow existing populations to expand. Attempts to translocate bell frogs to suitable breeding habitat have failed to establish self-sustaining populations but insights have been gained concerning husbandry, infection control and optimal field conditions for tadpole development.

Studies conducted since 1996 have confirmed the negative impact of predation by the exotic Plague Minnow *Gambusia holbrooki* on bell frog breeding success. Although fish predation is a prominent consideration when devising management plans for breeding habitat, our understanding of the role of this threat in regulating frog populations is still limited. The amphibian chytrid fungus *Batrachochytrium dendrobatidis* has now been recognized as an additional key threat to bell frog populations but research on this is in its infancy.

My attempt at a general synthesis to understand the dramatic decline of the Green and Golden Bell Frog suggests that habitat loss and fragmentation were the ultimate cause because they predisposed the species to the impacts of fish predation and disease. The species has persisted where multiple waterbodies, including those that are fish-free, occur within 1-2 km of each other. This provides a clue to conserving populations – it is likely that local population size and viability will be correlated with the number of available waterbodies. Progress to enhance the viability of key populations in each region has been slow. If this does not occur more quickly then extinction will prevail.

Key words: Green and Golden Bell Frog, *Litoria aurea*, population recovery, habitat fragmentation, gambusia predation.

Introduction

The Green and Golden Bell Frog *Litoria aurea* provides a cautionary tale to conservation biologists. It was once a conspicuous and abundant species throughout south-eastern Australia (Barker *et al.* 1995; Gillespie 1996; White and Pyke 1996) to the extent that it was collected for university class dissections and as food for captive snakes (Osborne *et al.* 1996; White and Pyke 1996, 1999). Despite this apparent abundance it declined precipitously during the 1980s, leading to its listing as an endangered species in New South Wales (NSW) in 1992 and as vulnerable by the Commonwealth in 1997 (Goldingay and Lewis 1999). By 1995 it was known from about 40 locations in NSW and few appeared to contain more than about 20 individuals (White and Pyke 1996).

Little research was conducted on the Green and Golden Bell Frog prior to 1990. Its listing in NSW led to it being considered in a number of development assessments; notably at Sydney Olympic Park and at Roseberry (Pyke and White 2001; Darcovich and O'Meara 2008; McFadden *et al.* 2008). With its listing came wider recognition that research was needed to address its conservation requirements. This led to a symposium being held in Sydney in 1995 to allow dissemination of recent research on this species and discussion of its conservation requirements. A proceedings of that symposium was published the following year (see Pyke and Osborne 1996). A second symposium on bell frog ecology and conservation was held in 2006 to disseminate research findings and promote discussion

of conservation actions. This symposium also included consideration of the threatened Southern Bell Frog *Litoria raniformis*.

The aim of this paper is to review what has been achieved by ecological research on the Green and Golden Bell Frog since 1996, as a way of both documenting its adequacy for informing management and as a way of identifying gaps in our understanding. A further aim is to attempt to provide a grand synthesis that may enhance our understanding of the factors responsible for the decline of this species and the possible solution to its conservation. While acknowledging that there is a considerable amount of information within the grey literature on this species (see Pyke and White 2001; White and Pyke 2008a), this paper relies on published studies because these provide a reliable measure of research activity, and peer-review prior to publication should guarantee the veracity of the results of such studies. This paper focuses on the Green and Golden Bell Frog but this and the Southern Bell Frog have much in common, so research on one can inform conservation of the other.

State of knowledge in 1996

In 1996 there were 14 papers published dealing with the ecology and one on the genetics of the Green and Golden Bell Frog (Fig.1). These studies covered about 7 broad topics. Five studies considered issues relating to distribution and abundance, while four provided reviews of management and conservation issues. This provided a reasonable starting point for recovery planning and for further research. Goldingay (1996) identified the kind of research additional to that presented in 1996 that was needed for the conservation of the Green and Golden Bell Frog. This included: habitat preference and use, population dynamics, a population viability analysis, experimental studies that control exotic fish predators, assessment of the role of translocation and genetics. Progress in a number of these research areas has been limited or non-existent. In the period 1997 to 2006, a further 22 studies were published. The main topics covered are reviewed below.
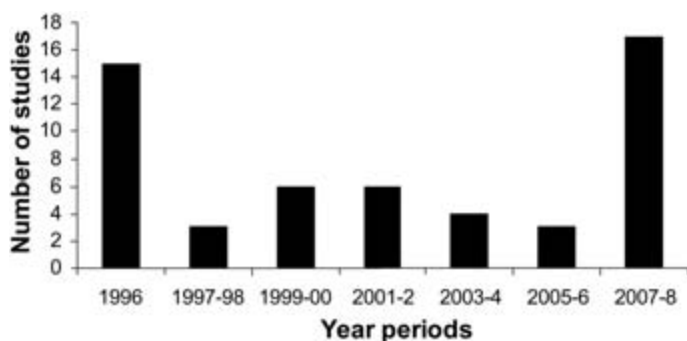

Figure 1. The number of studies published on the Green and Golden Bell Frog during the last 12 years.

Distribution and relative abundance

Several studies in 1996 examined the broad geographic distribution of the Green and Golden Bell Frog. White and Pyke (1996) provided a detailed account of 92 sites in NSW where the bell frog occurred historically. They documented surveys conducted since 1990 that revealed the species was present at only about 40 sites and that maximum count data suggested that all but four populations were very small in size. Osborne *et al.* (1996) documented the historic distribution of the Green and Golden Bell Frog, Southern Bell Frog *Litoria raniformis* and Yellow-spotted Bell Frog *Litoria flavipunctata/castanea* on the southern tablelands of NSW. They documented a widespread disappearance of all species. Lemckert (1996) reviewed surveys conducted by the State Forests of NSW that included many areas deemed suitable for the Green and Golden Bell Frog and where there were some historic records but none were found. In contrast, Gillespie (1996) documented the range of the Green and Golden Bell Frog in north-east Victoria. He concluded that the species was widespread in this region and that there was no evidence of a decline.

Since 1996, several studies have focused on particular regions. White and Pyke (1999) described the historic disappearance of bell frogs from the Bathurst-Orange area. Lewis and Goldingay (1999) conducted surveys and confirmed the disappearance of the Green and Golden Bell Frog from a number of locations in north-east NSW. Goldingay and Lewis (1999) conducted surveys in the Illawarra region and documented locations where the species still occurred. Wassens and Mullins (2001) conducted surveys near Queanbeyan and discovered what might be the only remaining bell frog population on the southern tablelands of NSW. Daly and Senior (2003) conducted surveys on the far south coast of NSW. Daly *et al.* (2008a) have completed detailed surveys at an important location on the south coast.

The draft recovery plan provided a very detailed account of the distribution and relative abundance of the Green and Golden Bell Frog throughout NSW (DEC 2005). This suggested that there were 43 populations and as many as 115 subpopulations. This provides an important starting point for recovery planning. Subpopulations were recognised to account for breeding sites that are physically isolated and among which frog dispersal may be infrequent. This has some merit but highlights how poor our current understanding is of bell frog migration and dispersal. It is somewhat contentious because it may suggest that a specific population has greater resilience than it really does. It highlights an area where further research is needed.

White and Pyke (2008a) have recently resurveyed all the known locations and have concluded that up to 8 of 31 populations have suffered local extinction. The status of several other populations remains unknown and some may also be extinct. Continued monitoring of populations must continue well into the future. Further reviews and collation of recent data have occurred for several populations in NSW (DEC 2007a,b,c,d,e,f,g).

Population ecology

No studies in 1996 dealt with aspects of population ecology but 13 have been published since then. Goldingay (1996) highlighted the need to describe population structure and dynamics at several sites. Initial studies attempted to describe population dynamics based on simple count data. At Port Kembla, the detection of frogs varied considerably

from night to night and inconsistently from site to site (van de Mortel and Goldingay 1998; Goldingay and Lewis 1999). Repeated surveys across different months can provide an index of relative abundance that can inform management priorities (Goldingay and Lewis 1999). Such surveys have allowed variation in the number of juvenile frogs to be documented, providing insights into the frequency and relative success of breeding at different sites (Goldingay and Lewis 1999). The highest single count was 422 juveniles at Coomaditchy Lagoon, whereas <15 juveniles were seen at each of four other sites.

Pyke and White (1999) used count data to reveal changes over a 3-year period in three artificial ponds at Homebush Bay. They found differences in the relative number of adult bell frogs at these sites. They observed no breeding at a permanent pond where the highest number of frogs was recorded. This was consistent with their earlier analysis of 74 bell frog sites, which revealed that breeding was significantly more likely to occur at sites with ephemeral ponds (Pyke and White 1996).

Permanent tagging of frogs allows more detailed information to be collected on the number of individuals present at a site and movements between captures. Christy (1996) first recognized the value of using passive integrated transponder (PIT) tags to mark bell frogs. Goldingay and Newell (2005a) used PIT tagging to provide a preliminary estimate of the number of bell frogs in a coastal lagoon in Yuraygir National Park (NP) in northern NSW. They tagged 147 frogs over a 6-year period and estimated the population to be at least 100 adult male frogs in the first year when more field work was conducted. Relatively few adult females were captured, suggesting either quite different habitat use to males or a highly skewed sex ratio (1 female:7.2 males). Breeding at this location was erratic and mostly associated with ephemeral ponds. At Port Kembla, Goldingay and Newell (2005b) tagged 244 adult frogs over a 4-year period at 3 waterbodies 0.5-2 km apart. They estimated the population to be at least 300 adult male frogs in the third year when more frogs were tagged. The sex ratio over the course of the study was 1:2.5, which suggests that at least 85 adult females were present. On Kooragang Island near Newcastle, Hamer and Mahony (2007) tagged 779 frogs from 32 waterbodies over two years. Their mean estimate of the adult male population size was at least 900 individuals.

Hamer and Mahony (2007) reported a sex ratio of 1:2.4, which is similar to that at Port Kembla. Whether the vastly different sex ratio at Yuraygir was due to a sampling bias or signals disfunction in a small population is unknown. Greer and Byrne (1995) recorded a 1:1 sex ratio in bell frog metamorphs from one location in Sydney. However, variation among locations may occur and differential mortality of the sexes as frogs mature may produce ratios that deviate from 1:1. There are few published data on sex ratio for Australian frogs because there have been few detailed studies of population ecology (see Lewis and Goldingay 2005). Understanding population sex ratios is important because this may allow better estimates of the female component of the population, which is what will ultimately influence population viability.

Pyke and White (2001) refered to unpublished data indicating that the population on Broughton Island may contain 1000 adults, and anecdotal evidence that Homebush Bay, Kurnell, Culburra, Meroo Lake, and Crescent Head each may also contain 1000 adults (but see Daly *et al.* 2008a). Knowing the size of different populations is central to recovery planning and may influence the priority given to management at a site. In some circumstances it may lead to on-site conservation being discontinued (e.g. Rosebery: see White and Pyke 1996, 2008b). Penman and Lemckert (2008) advocated the use of site occupancy models for monitoring populations but not all locations contain adequate numbers of waterbodies to use this approach (e.g. Yuraygir NP, Port Kembla) and absence of frogs from key breeding sites may be of great ecological significance rather than just statistical significance. Ultimately, conservation must be directed towards ensuring viable populations (Goldingay 1996; Goldingay and Lewis 1999). This will be informed by detailed information on the size of populations. Tagging studies may need to be repeated on a 5-10 year basis to gain a better understanding of population stability at key locations.

Three recent studies in which translocation and reintroduction of bell frog tadpoles have occurred employed visual encounter surveys and tagging to monitor recruitment of juvenile and adult frogs (Daly *et al.* 2008b; Pyke *et al.* 2008; Stockwell *et al.* 2008). These studies highlight the need for an understanding of bell frog dispersal behaviour.

Few data have been published on juvenile recruitment despite the critical importance of this to population dynamics. Pyke and White (1999) observed differences in the number of juvenile frogs (metamorphs) at three ponds at Homebush Bay, which partly reflected different breeding activity. Goldingay and Lewis (1999) recorded temporal variation in juvenile recruitment and vast differences among locations in Port Kembla. Goldingay and Newell (2005a) also recorded temporal variation in juvenile recruitment in Yuraygir NP. Temporal variation in rainfall was implicated by both studies as the factor causing variation in recruitment. O'Meara and Darcovich (2008) recorded variation in juvenile recruitment which reflected their imposed pattern of draining and refilling of ponds to control gambusia. Osborne *et al.* (2008) reported temporal changes in juvenile numbers within a season across three ponds. Daly *et al.* (2008a) recorded just 7 juveniles during surveys scattered over several years in south-east NSW.

Juvenile bell frogs are likely to incur high rates of mortality. There are several reports of adult bell frogs feeding on juvenile bell frogs at ponds (Miehs and Pyke 2001; Pyke and White 2001; White 2006). The significance of this is unknown, though artificial conditions may have some influence. The largest number of juvenile bell frogs reported is that at Coomaditchy Lagoon where 422 were counted on a single night following a count of 196 the previous day (van de Mortel and Goldingay 1998). No adult bell frogs were seen at night and few in the previous week. At Yuraygir, few adults were recorded in the areas where juveniles were seen (Goldingay and Newell 2005a). These observations serve to highlight how little is known of the behaviour of juvenile bell frogs.

Genetics

Understanding aspects of the genetics of a species is of key importance for a species' recovery (Colgan 1996; Burns *et al.* 2004). However, given the enormous amount of research that has occurred in this area, both empirical and theoretical, it is possible to some extent to generalize those findings for the recovery of threatened species when genetic data are absent. For example, populations reduced to small size are likely to be subject to inbreeding effects and ultimately reduced genetic diversity (Primack 1998). Populations that are isolated will be subject to genetic drift and if isolated for long periods of time are likely to diverge genetically from other populations (Primack 1998). Such populations are likely to show local adaptation to their environment. Therefore, species recovery can be guided by genetic principles until specific data become available. For example, concern should be expressed when populations are reduced to very small sizes due to the likely loss of genetic fitness. If individuals have to be translocated to augment populations or establish new ones, then loss of local adaptation can be overcome by limiting the distance over which individuals are moved (Colgan 1996; Goldingay 1996).

Burns *et al.* (2007) examined genetic structure in populations of the Green and Golden Bell Frog from across its geographic range. They found there was no phylogeographic structure, suggesting that historically there were no major barriers to dispersal. However, they also found that there was some structure among populations, with the more isolated populations showing genetic divergence (see also Burns *et al.* 2004). The Broughton Island population showed reduced genetic diversity, which was expected for a population that has probably been isolated for a long period of time. Burns *et al.* (2007) concluded that current levels of genetic diversity for the species were adequate but that if translocation was to occur for demographic reasons, then the highly differentiated populations (Broughton Island, Queanbeyan, Crescent Head/Yuraygir) should not be used as source populations. This confirms that some caution should be shown if employing translocation. Burns *et al.* (2004, 2007) urged the conservation of populations in close proximity to maintain genetic diversity and adaptive potential. These findings support the idea that management units scattered throughout the geographic range are appropriate. Furthermore, it would be prudent to also give the highly differentiated populations (Fig. 2) some management emphasis.

Habitat use

Bell frogs use habitats for breeding, foraging, shelter and hibernation. In 1996, descriptions of habitat use were confined to evaluating the attributes of breeding sites. Osborne and McElhinney (1996) described the basic attributes of five potential breeding sites on Bowen Island at Jervis Bay. Pyke and White (1996) collected habitat data for most breeding sites where Green and Golden Bell Frogs had been detected in NSW since 1990. This included physical attributes (e.g. size of water body, level

Figure 2. A frog from the Yuraygir National Park population showing the predominance of brown colouration that characterizes this population.

of disturbance) as well as biotic ones (e.g. plant species, presence of Plague Minnows *Gambusia holbrooki*). They differentiated between sites where breeding was known and not known. Their statistical analysis identified ephemeral waterbody and absence of predatory fish as important for breeding. They described a set of attributes that commonly occurred at sites with bell frogs and used this to recommend attributes for sites being managed for bell frogs. Some limitations of this study were described by Hamer *et al.* (2002a).

Pyke and White (2001) noted that most earlier accounts of the habitat used by bell frogs were so general that they encompassed most waterbody types. Pyke *et al.* (2002) provided a basic description of biotic and abiotic habitat variables for breeding sites in NSW, Victoria and New Zealand. They found a preference for small ponds that were either ephemeral or where the water level fluctuated greatly. They concluded that despite some common habitat features (e.g. emergent vegetation), bell frogs could tolerate sites without such features. Basic descriptions of habitat at breeding sites were provided for Yuraygir NP (Goldingay and Newell 2005a) and for Port Kembla and other Illawarra sites (Goldingay and Lewis 1999; Goldingay and Newell 2005b).

Hamer *et al.* (2002a) described habitat at 43 waterbodies on Kooragang Island near Newcastle. They compared numerous biotic and abiotic habitat variables for waterbodies with and without bell frogs. They found that the presence of adult bell frogs at waterbodies was explained statistically by the greater abundance of certain plants (e.g. *Juncus kraussii*), and these plants were also favoured for basking and foraging. They also noted that whether a waterbody was occupied was partly dependent on proximity to other waterbodies.

Hamer *et al.* (2002b) noted that the recent literature on bell frogs had suggested that fish-free ephemeral waterbodies were the optimal breeding habitats, but early accounts (e.g. Courtice and Grigg 1975) considered permanent ponds to be optimal. To test

this notion they conducted a laboratory experiment in which they manipulated water volume and presence of plague minnows. Although such an experimental approach has merit, it is unlikely they adequately simulated an ephemeral waterbody or the presence of predatory fish. They found that bell frog tadpoles did not respond to these stimuli with accelerated development and concluded that ephemeral waterbodies were suboptimal. They also suggested that bell frogs appear to have "no history of co-existence with fish". This observation seems to derive from Victoria where bell frogs occur in fish-free waterbodies (Gillespie 1996). However, it conflicts with observations of large native fish populations in permanent waterbodies occupied by bell frogs in north-east NSW (Goldingay and Newell 2005a). The negative impact that exotic and native fish can have on bell frog tadpoles suggests that fish have always played a key role in the use of breeding habitats but this is not well understood. That male bell frogs on Kooragang Island moved more often to ephemeral waterbodies than expected based on availability (Hamer *et al.* 2008) suggests that ephemeral ponds do play an important role in the breeding strategy. Indeed, over a 3-year period Pyke and White (1999) only recorded male calling and bell frog tadpoles in two ephemeral ponds and not in a permanent pond, despite a greater number of adult bell frogs being observed at the permanent pond.

Hamer *et al.* (2003) conducted an experiment in outdoor enclosures to assess winter retreat site selection by juvenile bell frogs. Frogs were provided with piles of bricks with varying size gaps between bricks and varying amounts of sun exposure. They found a preference for sheltering in small gaps and to bask when aquatic habitat was provided.

Despite some advances in our understanding of habitat preference and habitat use in the last 12 years, the way frogs use habitat features in the field is still poorly described. Because a large part of the bell frog lifecycle is geared towards breeding and therefore breeding sites, breeding habitat is typically treated as synonymous with habitat. Bell frogs are often seen basking at breeding sites, which reinforces the notion that this species is dependent on waterbodies for all it resources. This is not true because it appears that females spend a considerable amount of time away from breeding sites. What habitats and microhabitats they use and whether located nearby or well away from breeding sites are largely undocumented. There is a need to describe diurnal refuge sites and winter hibernation sites. Describing these at natural and artificial sites will be useful to management. The characteristic diurnal basking behaviour of bell frogs (Pyke and White 2001) is poorly understood. Hamer *et al.* (2003) suggested that basking allows growth rates to be maximised. There is also a need to describe the use of microhabitats by juvenile frogs. The focus on breeding sites has been of considerable value to management but the overall conservation of this species will be enhanced by an increased understanding of the use of other habitat elements.

Movement patterns

Knowledge of the spatial movements of bell frogs is critical to habitat restoration and to understanding their population dynamics. The distances moved by bell frogs can be described based on the recapture of tagged individuals or from radio-tracking. Pyke and White (2001) reported that one individual that was followed at night as it foraged moved 1.5 km. They also reported movements by tagged individuals of 2-3 km. Christy (2001) recorded maximum distances moved by tagged frogs at Homebush Bay and Kurnell of 632 m and 450 m, respectively.

In Yuraygir NP, Goldingay and Newell (2005a) found tagged male frogs moved 300-500 m from a permanent lagoon, where they were first captured, into ephemeral ponds that formed after heavy rain. At Port Kembla, one adult female moved 1.25 km between breeding sites over a 14-month period (Goldingay and Newell 2005b). Surprisingly, none of 204 tagged frogs were known to have moved between two sites separated by about 500 m of essentially open ground. It seems unlikely that these two sites were effectively isolated.

Hamer *et al.* (2008) provided a detailed description of bell frog movements (112 male, 14 female) among waterbodies on Kooragang Island. Approximately 50% of movements were to the nearest waterbody (~50 m away). Males moved significantly further when moving to an ephemeral waterbody (mean = 220 m) compared to a permanent waterbody (mean = 142 m). The maximum movement distances were 1100 m for a male and 360 m for a female. The use of ephemeral waterbodies coincided with periods of heavy rain. The relative value of such movements and habitat use are unknown but part of the breeding strategy is likely to involve >1 spawning event by females and depositing eggs at different sites as a form of bet-hedging. Permanent and ephemeral waterbodies will differ in their nutrient and predator status, and recruitment success from these sites may show interannual variation.

At present, little is known of the dispersal behaviour of juvenile bell frogs. However, it is of considerable importance to management. It has relevance to translocation where the focus has been on using tadpoles (see Daly *et al.* 2008b; Pyke *et al.* 2008). Juvenile frogs may persist around breeding sites for some weeks after metamorphosis. van de Mortel and Goldingay (1998) described one mass breeding event at Port Kembla when >400 juveniles were present in vegetation surrounding Coomaditchy Lagoon. Many metamorphs were observed dispersing across the roadway 100 m away from the lagoon, including one that retained a tail longer than its snout-vent length. Another juvenile was observed 700 m from the lagoon, which was the closest breeding site (Goldingay and Lewis 1999). O'Meara and Darcovich (2008) observed juveniles around ponds where no tadpoles had been present, indicating that dispersal to these ponds had occurred. In Yuraygir NP, Goldingay and Newell (2005a) observed a decline in the number of metamorphs around an ephemeral pond over several weeks, suggesting dispersal away from the breeding sites. Where these individuals disperse to is unknown. Understanding this behaviour will provide a better understanding of population processes.

Threats to recovery

Reversing the decline of a threatened species is dependent on identifying the causes of that decline (Caughley and Gunn 1995; Goldingay 1996). An experimental approach is usually required to demonstrate that a factor has the ability to influence population processes. Two factors (exotic fish predation, ultraviolet-B (UV-B) radiation) received experimental assessment in 1996. Other factors such as habitat alteration were implicated from descriptive studies. Since then, other factors such as a fungal disease (chytridiomycosis) and increased use of fertilizers have received some attention. These factors are described below. Fish predation has received more attention so is treated in greater detail.

UV-B radiation

In the mid-1990s, concern arose that an increase in UV-B radiation due to ozone depletion may have been the cause of the global decline in amphibians (Blaustein *et al.* 1994). Declining species were more susceptible to DNA damage and may have lower levels of enzymes (photolyase) that would repair such damage. This impact was most likely mediated through reduced hatchability of eggs. van de Mortel and Buttemer (1996) conducted field experiments with eggs of the Green and Golden Bell Frog, Brown Tree Frog *L. dentata* and Peron's Tree Frog *L. peroni*. Although bell frog eggs had lower hatching success compared to the other species (46% vs. 76%), van de Mortel and Buttemer concluded that the lack of a difference among treatments suggested that UV-B was not the cause of the decline. The much higher clutch size in the bell frog (2-11,000; Pyke and White 2001; White and Pyke 2002) compared to the other species (*L. dentata*: 250-1900, *L. peroni*: 500-1900; van de Mortel and Buttemer 1996) would also compensate for lower hatchability.

van de Mortel *et al.* (1998) determined photolyase activity for the above three species. Although that of the bell frog was considerably lower than for the other two species, relative hatching success for unfiltered light divided by that for UV-B filtered light did not differ. van de Mortel and Buttemer (1998) conducted lab studies that investigated the behavioral response of tadpoles and frogs of the three species in an arena providing a choice between one half with high levels of UV-B radiation and the other where 100% of UV-B was blocked. Bell frog tadpoles preferred the UV-B free area but adults showed no preference. van de Mortel and Buttemer concluded that the ability of bell frogs and tadpoles to detect and respond to peaks in UV-B was unlikely to explain its decline.

One issue that has not been well documented for this factor is that in the north American species in which UV-B has been implicated as a factor in the decline of amphibians, the egg stage of the life cycle can last >20 days (van de Mortel *et al.* 1998). That is, there is an extended period over which the eggs may be vulnerable to impacts of UV-B. In contrast, the eggs of bell frogs hatched within about 3 days of deposition (van de Mortel

and Buttemer 1996), and they do not remain on the surface of the water, so the period over which they would be exposed to UV-B is very short. It's also documented that dissolved organic matter may ameliorate the effects of UV-B on eggs and larvae of amphibians (Beebee and Griffiths 2005). Thus, it seems unlikely that this factor has been important to the decline of the bell frog.

Habitat alteration

It is widely acknowledged that freshwater wetlands have been extensively modified in NSW (Goodrick 1970; Daly 1996; White and Pyke 1996; Goldingay and Lewis 1999; Lewis and Goldingay 1999; DEC 2005). Goodrick (1970) estimated that 60% of the wetlands in NSW had been extensively modified or reclaimed by 1969. This situation must have had an impact on populations of bell frogs and cannot be ignored as a contributing factor in the decline of this species. Pyke and White (2001) observed that most of the sites where the species is now found in NSW and Victoria are largely human-made. This situation has probably arisen because such sites are all that remain in areas of former breeding habitat of the bell frog (Goldingay 1996).

Wetlands on the Illawarra Coast have been removed, fragmented and extensively modified (Chafer 1997; Goldingay and Lewis 1999). The BHP steelworks in Port Kembla sits astride a former wetland. Sand-mining has also greatly modified wetlands in this area (Chafer 1997). Bell frog sites through the Illawarra are impacted by residential and industrial development, and roads. Wetlands on the far north coast have fared somewhat better but many have been lost and many impacted by extensive sand mining (Clancy 1996; Lewis and Goldingay 1999; Goldingay and Newell 2005a).

There has been no direct assessment of the impact of habitat alteration on bell frog populations but it is likely there is still an on-going influence. The likely impact of habitat fragmentation can be inferred from studies that demonstrate that bell frogs have persisted where waterbodies are in close proximity to each other (Goldingay and Lewis 1999; Hamer *et al.* 2002a). This suggests that the isolation of and a reduction in the number of local breeding sites is likely to compromise population viability because it leads to reduced local population size and increases dispersal distance. Research that provides a more detailed understanding of habitat loss and fragmentation would greatly inform attempts to conserve and restore habitat of this species.

Christy and Dickman (2002) investigated the tolerance of tadpoles to various levels of salinity, stating that rising salt in coastal localities as a consequence of changes to landscapes was a potential threat to bell frog breeding sites. They found that tadpoles tolerated 4% seawater but above that there was a significant reduction in growth and increased mortality. Salinity of 10% seawater and above caused total mortality within several days. Detailed field data are required to determine the extent that this might be a management issue.

Increased fertilizer use

Hamer *et al.* (2004) hypothesised that an increase in fertilizer use from the 1960s through the 1970s had led to a build up of fertilizer that was washed into waterbodies after heavy rain and this resulted in mass mortality of tadpoles. Rainfall in 1974 was exceptionally high (43% higher than average) and occurred in the year after the peak in superphosphate application. This coincided with the period in which there was a decline in the reporting of bell frogs in the NSW Wildlife Atlas. Hamer *et al.* (2004) went on to conduct lab experiments in which tadpoles of three species, including bell frogs, were exposed to ammonium nitrate and calcium phosphate fertilizers. They found that bell frog tadpoles alone had higher mortality at the higher concentrations of these fertilizers. However, average survival of bell frog tadpoles was still high (>75%) and higher than that of the common froglet *Crinia signifera* in all treatments for both fertilizers. Survival of froglet tadpoles was less than 50% in 3 of 8 treatments. These differences weaken any conclusions about the effect of fertilizer.

Chytrid fungus

Due to the coincidence of precipitous declines in the abundance of many species of amphibian around the world, a common cause had long been hypothesized (e.g. Laurance *et al.* 1996). The agent that was eventually implicated as having a global impact was the amphibian chytrid fungus *Batrachochytrium dendrobatidis* (Berger *et al.* 1998). The disease this causes is chytridiomycosis, which manifests itself as lethargy, skin discolouration, excessive sloughing of skin and ultimately death (Berger *et al.* 1999). Despite this disease being implicated in the decline and extinction of 14 Australian rainforest frogs (Retallick *et al.* 2004), the role of the chytrid fungus in the decline of the Green and Golden Bell Frog is not well documented, but the disappearance of this species from locations where other causal agents could not be implicated (Osborne *et al.* 1996; Mahony 1999) suggests it has had an impact. Infection by chytrid fungus was listed as a key threatening process nationally in 2002 and in NSW in 2003.

Penman *et al.* (2008) observed a mortality event at Sydney Olympic Park in one month, in which 17 of 23 dead bell frogs tested positive for chytrid. Despite this, bell frog counts remained at equivalent levels throughout an 8-year period. Stockwell *et al.* (2008) conducted an introduction of 850 bell frog tadpoles into a fenced area containing 3 ponds. Metamorphosis occurred in a high percentage of tadpoles, leading to counts of 10-25 juveniles around the ponds in the subsequent 2 months. Few bell frogs appeared to survive beyond 8 months. Six bell frogs were found dead 3-5 months after metamorphosis and 4 of 5 of these tested positive for chytrid. Furthermore, 53% of 60 live bell frogs tested positive for chytrid in that period. Chytrid infection was implicated as the cause of the failure of this introduction. Chytrid has not been implicated in two other re-introductions. Daly *et al.* (2008b) observed few adult bell frogs 1-2 years after the release of 6000 bell frog tadpoles. Chytrid was identified in *Litoria verreauxii* and *Limnodynastes peronii*

approximately 1 km from the release site but not in any frogs at the release site. Pyke *et al.* (2008) observed 45 bell frogs (>48 mm snout-vent length) after the release of approximately 9,000 bell frog tadpoles over several years. They reported no signs of diseased frogs and implicated other factors in the poor results.

In other studies, properties of the aquatic environment have been postulated as bestowing protection from chytrid infection. Daly *et al.* (2008a) found that 12 bell frogs tested negative for chytrid at Meroo National Park and suggested that sulphur in the sediment of the lakes where frogs occur may confer some benefit in precluding the fungus. Osborne *et al.* (2008) described the occurrence of a highly restricted bell frog population on the Southern Tablelands where other populations disappeared in the 1980s. They suggested that heavy metal contamination of the Molonglo River and floodplain from a mine tailings dam may confer fungicidal benefits to the frogs in this system of waterbodies. Sick-looking specimens of bell frog from the upper floodplain have tested positive for chytrid. Similarly, Threlfall *et al.* (2008) postulated that the persistence of bell frogs at several former industrial sites in Sydney and Port Kembla, where heavy metal concentrations exceed environmental standards, could be due to the fungicidal properties of heavy metals. It is possible also that salt may confer fungicidal benefits. White (2006) documented the death of several adult bell frogs that tested positive for chytrid infection from the site of the Marrickville Community Nursery. Tadpoles raised at Taronga Zoo had been released into a 3 m diameter pond at the site. The salinity in the pond was raised to 3% sea water and 40 tadpoles released. Two months later 33 juvenile frogs were present. No chytrid-related deaths were detected.

Further research is needed to understand the frequency of chytrid infection in different bell frog populations. This needs to be coupled with research that aims to mitigate the impact of the fungus (e.g. White 2006). The seriousness of chytrid infection across the range of the Green and Golden Bell Frog is poorly known and this will hamper most recovery efforts. Kriger and Hero (2006) reported the apparent ability of Stony Creek Frogs *Litoria wilcoxii* in south-east Queensland to clear their chytrid infections. Beebee and Griffiths (2005) have highlighted some inconsistencies in infection frequencies and decline or survival. They suggest it remains unclear whether the fungus is a primary or secondary cause of amphibian declines.

Influence of fish on bell frog breeding

Impacts from Plague Minnows

Predation by the Plague Minnow (hereafter gambusia) was implicated in the decline of the Green and Golden Bell Frog by many authors in 1996 (see Daly 1996; Goldingay 1996; White and Pyke 1996). Morgan and Buttemer (1996) conducted various experiments in the lab and in the field, in which they observed high mortality of bell frog tadpoles in the presence of gambusia. Mahony (1996) noted some negative association of bell frogs

with gambusia in the field while Pyke and White (1996) reported that breeding was more likely where predatory fish were absent. Gillespie (1996) found no apparent decline by bell frogs in East Gippsland where gambusia was absent.

Subsequently, further studies have demonstrated that gambusia has a negative effect on bell frogs and their tadpoles but the presence of several sites where bell frogs breed in the presence of gambusia has led some authors (e.g. Mahony 1999) to conclude that gambusia predation is not a complete limiting factor. A negative association between bell frogs and gambusia has been found at sites on the NSW north coast (Lewis and Goldingay 1999) and on the Illawarra coast (Goldingay and Lewis 1999). Pyke and White (2000) conducted numerous predation experiments on bell frog tadpoles. They concluded that gambusia was a voracious predator on tadpoles and suggested that the few sites where the two co-exist may provide insights for managing impacts from gambusia. Pyke and White (2001) noted that gambusia was present at 77 of 86 sites where bell frogs disappeared prior to 1990 where habitat destruction had not occurred. They suggested there was a need to determine what allowed bell frogs to breed in waterbodies with gambusia. Pyke *et al.* (2002) also noted a negative association of bell frogs with gambusia. In New Zealand they found bell frogs at 6 of 10 sites without gambusia but none of 3 sites with gambusia. In Victoria, gambusia was absent from 41 sites where records of bell frogs occurred.

Coomaditchy Lagoon near Port Kembla has become well known for the occurrence of bell frog breeding in the presence of gambusia. In documenting this situation van de Mortel and Goldingay (1998) postulated that submergent vegetation may have allowed tadpoles to escape predation. On Kooragang Island, Hamer *et al.* (2002b) noted breeding by bell frogs in 3 of 36 ponds with gambusia, and 1 of 7 without. Adult bell frogs were present at 16 of the waterbodies with fish. They concluded that breeding was not determined by the presence of gambusia. They found that the abundance of certain plants explained the presence of adult bell frogs at waterbodies. It was unclear why breeding occurred in just 4 ponds when many more were occupied by adult frogs.

Recent studies confirm the negative impact that gambusia has on bell frog tadpoles. Pyke *et al.* (2008) conducted a translocation of bell frog tadpoles to ponds at Long Reef Golf Course. During the initial release they were unaware that several ponds had gambusia or native fish present. Subsequent surveys detected tadpoles only in fish-free ponds. Gambusia colonised created ponds at Botany and prevented the survival of translocated tadpoles (White and Pyke 2008b). O'Meara and Darcovich (2008) described the control of water levels in ponds specifically constructed for bell frogs at Sydney Olympic Park. These ponds had inadvertently become colonised by gambusia from an adjoining creek. Connection of each pond to a water reticulation system enabled a management regime in which approximately one-third of the 22 ponds was drained over a 1-week period in three consecutive years. A different set of ponds was drained each year and remained gambuisa-free, with one exception, for 2-5 months. Tadpoles, including those of bell frogs, were observed in ponds on 17 of the 22 occasions they were fish-free but on only 3 of 44 occasions for those that were not drained in a given year and contained fish. The dispersion of juvenile frogs across the ponds was only partly aligned with those that had been drained, while adults were even less aligned with the fish-free status of the ponds.

The conclusion to be drawn from existing studies is that gambusia does prey on bell frog tadpoles and is almost certain to be regulating population size and recovery by bell frogs in NSW. Noting that bell frog breeding and persistence has occurred at sites with gambusia (e.g. White and Pyke 2008a) does not demonstrate a lack of impact from fish predation but that some site conditions may partially reduce the impact. Furthermore, the presence of adult bell frogs at ponds containing fish cannot be used as evidence that fish are not regulating bell frog abundance. That bell frogs have disappeared or are absent from sites without gambusia confirms that other factors have had a role in the decline of this species and may continue to prevent its recovery (see above).

Gambusia predation was listed in NSW as a key threatening process in 1999. A Threat Abatement Plan was published in 2003 (NPWS 2003). This introduced many procedural changes but at present has not led to any significant developments at bell frog sites that may promote recovery. Given that gambusia is so widespread there should be no complacency in attempting to mitigate its likely impact on frog populations.

Co-occurrence of bell frog breeding and gambusia at Port Kembla

Sites with gambusia where bell frogs have bred can offer important insights to the impact of this fish and how this may be reduced. Gambusia occurs at both Coomaditchy Lagoon and Korrongulla Wetland in Port Kembla but at a higher density at the former site (Goldingay and Lewis 1999). Over a 3.5-year period 20-63 adult bell frogs were counted at night in 2-month census-periods at Coomaditchy (Fig. 3). Juvenile bell frogs were observed during 6 of 7 census-periods, with large numbers (>100) observed in two census-periods. During the same 3.5-year period small numbers of adults were detected at Korrongulla (located approximately 2.5 km south of Coomaditchy). Only three juveniles were ever detected at Korrongulla (Fig. 3). The permanent ponds at Korrongulla have resulted from sand-mining and are steep-sided and provide little scope for avoidance of predation by fish. The one ephemeral pond there received water and fish from the permanent ponds during extreme rainfall events. It appears that fish predation is limiting population size at this site.

How do bell frogs at Coomaditchy successfully reproduce in the presence of gambusia? Observations of dense mats of potamogeton during spring (Goldingay pers. obs.) led van de Mortel and Goldingay (1998) to postulate that aquatic vegetation enabled tadpoles to avoid predation. Further observations at Coomaditchy led
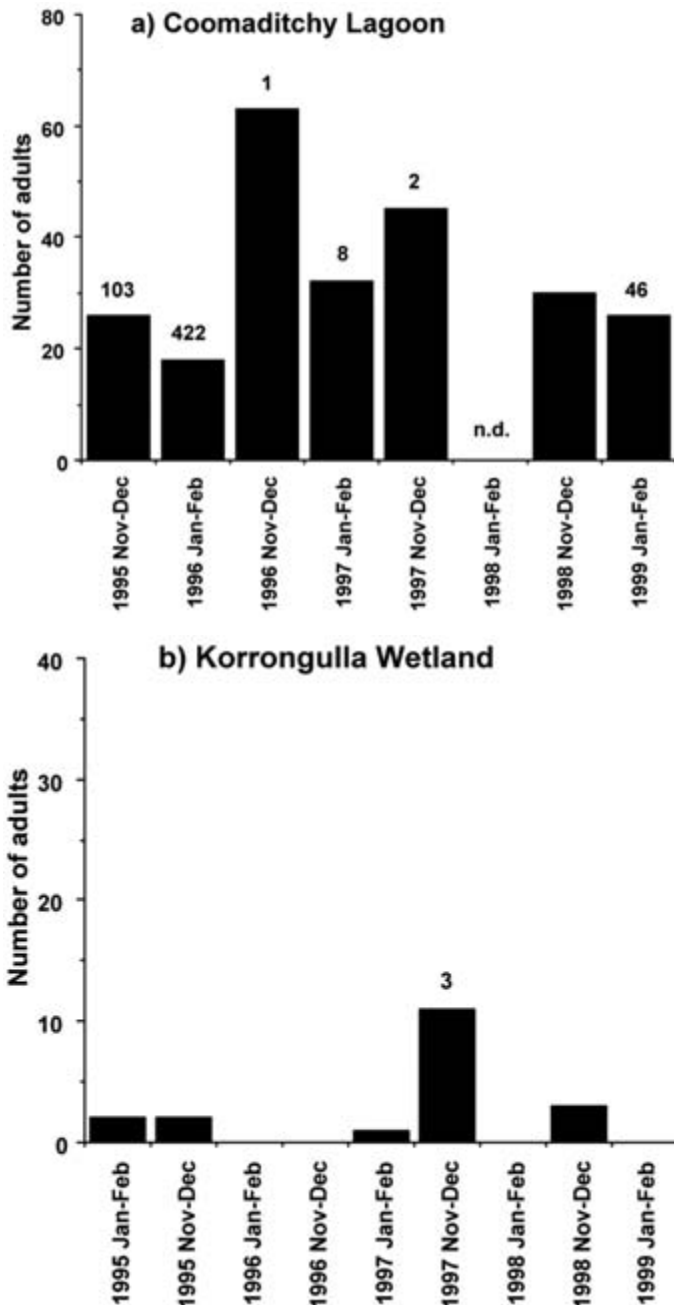
a) Coomaditchy Lagoon

Figure 4. Flooding at Coomaditchy Lagoon approximately 1 week after an extreme rainfall event in October 1998. The high water mark for this event can be seen as a line of debris on the grass behind the sign.

Data were collected 1 week (16 Feb), 3 weeks (4 Mar), 5 weeks (18 Mar), and 8 weeks (7 Apr) after the rainfall event. During each period, dip net sampling was conducted after dark along the northern side of the lagoon at 10-m intervals over a distance of approximately 150 m, heading from the western end to the eastern end (i.e. 12-15 sampling points). At each sampling site three microhabitats were sampled: water <10 cm in depth, water 20-30 cm in depth and open water (ca. 1 m deep). These are referred to as shallow, middle and deep-water zones. Sampling at each site consisted of dragging the net (30 cm dia.) through a single straight scoop and counting the number of tadpoles and fish retained in the net.

During week 1, the number of fish in the 3 zones was extremely low (Fig. 5). By week 3, the number in the middle zone had increased substantially and doubled over the next 5 weeks. The number in the shallow zone was still low after 3 weeks but was as high as the middle zone by week 5. It is assumed that outside an extreme rainfall event fish numbers in the three zones would be at least at the levels recorded in week 8. Most tadpoles occurred in the shallow zone across the eight weeks of sampling (Fig. 5). The number was high in week 1 but by week 3 had decreased by over 50%. Tadpoles stayed amongst the grass within the shallow zone as the water's edge retreated back to the usual lagoon edge. It appeared that the grass was providing retreat sites to the tadpoles. These observations suggest that mortality of tadpoles was substantial in the first few weeks (few could metamorphose within 4 weeks) and coincided with an increase in fish numbers, though waterbirds are also likely to have contributed to the decline.

There is a need for much more research to be done to better understand the interaction between bell frog tadpoles and fish. The above data demonstrate the unusual circumstances that allow breeding to occur at Coomaditchy Lagoon. They highlight the reliance on uncommon rainfall events for tadpoles to have any chance of surviving and add support to the hypothesis that above average rainfall is required for juvenile recruitment to occur.
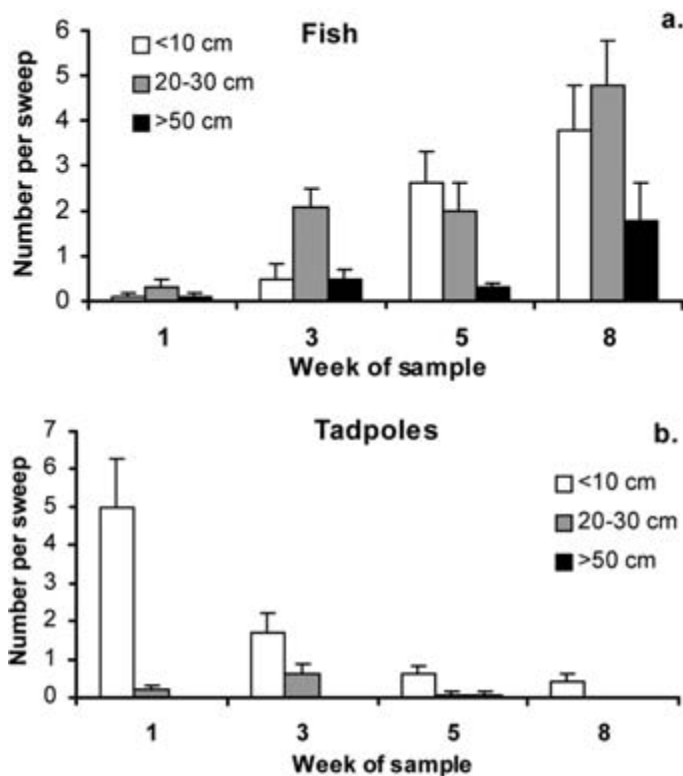
Figure 3. Maximum single night counts of adult frogs around Coomaditchy Lagoon and Korrongulla Wetland. Values above bars are the maximum single counts of juvenile frogs. Source: Goldingay and Lewis (1999).

Goldingay and Lewis (1999) to postulate that variable recruitment events were mediated by above average rainfall that provided conditions enabling tadpoles to evade predation. They suggested such rainfall caused water in the lagoon to spill into the surrounding grassy area, which provided protected sites for spawning and retreat sites for tadpoles.

I tested this hypothesis by collecting data on tadpoles and fish following an extreme rainfall event in early February 2002. During a previous but similar event, water from the lagoon extended well into the surrounding grassy area but after one week had retreated several metres (Fig. 4) and continued to recede over further weeks.

Figure 6. North-western side of Coomaditchy Lagoon in 1998 showing extensive beds of spikerush.

Figure 5. The number (±se) of a) exotic fish (*Gambusia holbrooki*), and b) tadpoles (both *L. aurea* and *Lim. peroni*) detected in single sweeps of a dip-net in Coomaditchy Lagoon beginning on 16 February 2002.

In 2004, several carp *Cyprinus carpio* were apparently intentionally introduced to Coomaditchy Lagoon. This has coincided with the disappearance of spikerush *Eleocharis sphacelata* from the lagoon (Figs 6, 7). Few bell frogs have been seen there since (Gaia Research 2008). It will be difficult and expensive to remove carp from the lagoon. A simpler approach is to provide a series of small ponds that are ephemeral or which could be easily drained adjacent to the lagoon. Adult frogs could use the lagoon for shelter and foraging but move to the small ponds to breed.

Impacts of native fish

Native fish may also limit the breeding success of bell frogs. Bell frogs in Victoria occupied permanent waterbodies where native fish were absent (Gillespie 1996). Pyke and White (2000) noted that native fish may prey on bell frog tadpoles but they did not consider this a serious situation. Permanent waterbodies in Yuraygir NP in north-east NSW contained many species of native fish, including empire gudgeon *Hypseleotris compressa*, firetail gudgeon *Hypseleotris galli*, mullet *Mugil cephalus*, pacific blue-eye *Pseudomugil signifer* and eel *Anguilla* sp. (Goldingay and Newell 2005a). Observations suggest that bell frogs do not breed successfully in Blue Lake and poorly in a swamp connected to it where native fish also occur (1-8 metamorphs observed across 5 years), though fish numbers appear to fluctuate seasonally. Juvenile bell frogs were detected during only 3 of 7 observation periods when adult numbers frequently exceeded 20 individuals (Fig. 8). This contrasts markedly with the observations at Coomaditchy (Fig. 3). The most successful

Figure 7. North-western side of Coomaditchy Lagoon in 2008 showing no beds of spikerush. This loss is attributed to the deliberate introduction of carp into the lagoon.

breeding event recorded in Yuraygir NP occurred in an ephemeral pond where fish were absent. Pyke *et al.* (2008) released hundreds of bell frog tadpoles into two ponds that contained native fish (*Galaxia maculates* and *Anguilla australis*) and other fish-free ponds. Subsequent monitoring revealed tadpoles and metamorphs only at the fish-free ponds. Daly *et al.* (2008a) recorded few bell frog metamorphs at sites with native fish on the NSW south coast where adult bell frogs occurred.

These observations suggest that bell frogs may experience poor breeding success where any fish are present and they may be quite dependent on ephemeral ponds. Further field studies that consider the impact of native fish on bell frog tadpoles are likely to provide important insights that can influence a range of management actions at bell frog sites.

An hypothesis for bell frog declines and disappearances

There has been much speculation and discussion over the years about the causes of the decline of the Green and Golden Bell Frog (Goldingay 1996; Mahony 1996, 1999; Osborne *et al.* 1996; White and Pyke 1996). Many
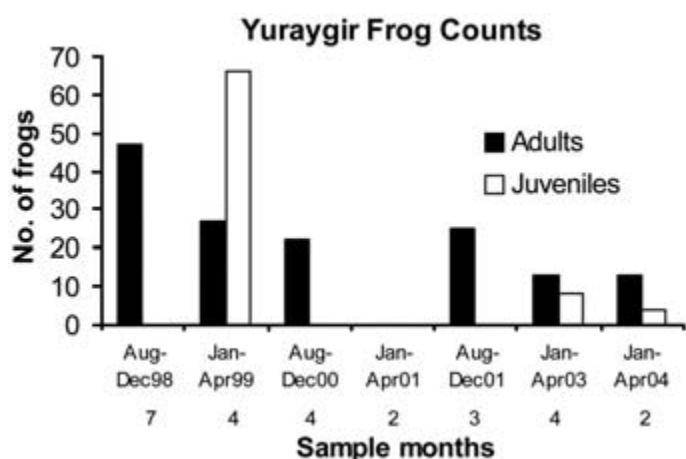
Yuraygir Frog Counts

Figure 8. Number of adult bell frogs tagged in Yuraygir NP and number of juvenile frogs counted around waterbodies. The number of survey nights is shown below each period. Source: Goldingay and Newell (2005a).

have sought a single explanation but exceptions readily occur that has led to questioning of specific hypotheses. For example, gambusia has been absent from a number of sites where bell frogs have disappeared (Osborne *et al.* 1996; Mahony 1999).

Here I review information provided by a number of authors to identify some broad patterns in the decline and disappearance of several bell frog species. I believe there are many similarities in the decline of these species that provide important insights for conserving populations of both Green and Golden Bell Frogs and Southern Bell Frogs. The proximate cause of the declines appears to be several factors but one factor may be the ultimate cause.

Southern Tablelands extinctions

Osborne *et al.* (1996) reviewed information on the distribution and abundance of bell frogs from a small number of sites around the Australian Capital Territory (ACT) and the Southern Tablelands. For areas above 400 m elevation, museum specimens documented 15 locations for the Green and Golden Bell Frog, 23 locations for the Southern Bell Frog and 10 locations for the Yellow-spotted Bell Frog (*L. castanea*). From 68 frog choruses recorded at different locations during late September to October in 1975 and 1976, five included Green and Golden Bell Frogs, five included Southern Bell Frogs and three included Yellow-spotted Bell Frogs (Osborne *et al.* 1996). These data suggest that there were relatively few locations at which any of the three species occurred. Although it was reported that these species were abundant at individual sites (described as "large numbers"), it appears that many of the locations were widely spaced. Humphries (1979) observed bell frogs at one ACT site containing 6 ponds where he reported there were <30 adult Green and Golden Bell Frogs and <5 female Yellow-spotted Bell Frogs. One could conclude from these descriptions that both of these species had small ranges on the Southern Tablelands and their populations were characterized by small sizes. Gambusia was absent from many sites where bell frogs occurred (Osborne *et al.* 1996).

Northern Tablelands extinction

Mahony (1999) documented the small geographic range of the Yellow-spotted Bell Frog, centred around Guyra. There are just 13 sites in this area from which it was known based on museum specimens. The species was reported to be reasonably abundant with 42 individuals lodged with the Australian Museum collected on a single day (Mahony 1999). Gambusia is now abundant on the New England Tablelands.

Central Tablelands extinctions

The Green and Golden Bell Frog occurred historically at a small number of sites associated with the Macquarie River near Bathurst (White and Pyke 1999). The species was sufficiently abundant at several locations that it was collected as a food item for captive snakes. It appears that gambusia was not well established in the area until the late 1960s, which coincided with increased drainage of the floodplain that removed known bell frog breeding sites. The Green and Golden Bell Frog disappeared from the Bathurst area in the early 1970s (White and Pyke 1999). The Yellow-spotted Bell Frog was known from three locations in the Bathurst-Orange area (White and Pyke 1999). The record near Orange was made in 1977 and consisted of 10 frogs. White and Pyke (1999) also suggest that the records of local herpetologists indicate that the Southern Bell Frog occurred at three locations near Bathurst.

Synthesis

The observations on bell frogs from the tablelands areas suggest that these species occurred at a relatively small number of sites and few appeared to be characterized by large local population sizes. Their demise on the Central Tablelands coincided with habitat loss and increased prevalence of gambusia. Mahony (1996, 1999) pondered differences in rainforest frog declines and bell frog declines, and noted that the main similarity was high elevation. Hero *et al.* (2005) analysed the ecological traits of Australian upland frogs to determine whether any traits could explain the decline of species. They collated data for 40 upland species of which 20 had declined. They found that declining species were significantly characterized by small range size and small clutch size. Murray and Hose (2005) examined life history traits of 148 Australian frogs to determine whether any traits were associated with declining species. They found that species with narrow geographic ranges were predisposed to decline but clutch size was not correlated with decline.

Small range size is a trait shared with the Yellow-spotted Bell Frog. Although this species is now recognized to have occurred on the Southern, Northern and Central Tablelands of NSW (Thomson *et al.* 1996; White and Pyke 1999), its geographic range was highly disjunct and quite restricted in these regions. The Green and Golden Bell Frog also had a restricted range on the Southern and Central Tablelands where it occurred. Thus, because a narrow geographic range predisposes a species to decline, small disjunct segments of ranges are likely to predispose a species to at least local extinction. Geographic range size

is strongly correlated with abundance in Australian frogs (Murray *et al.* 1998). In general, species with large ranges occur at a larger number of sites and are more abundant than those with small ranges (e.g. Gaston *et al.* 2000). Thus, they are likely to be associated with bigger total population sizes. This may allow local populations to be rescued by dispersal if they become extinct. Therefore, the small ranges (or segments of ranges) of bell frogs occurring in tableland areas fostered susceptibility to decline due to low population size.

Bell frogs have large clutch sizes (Pyke and White 2001; Pyke 2002; White and Pyke 2002), which is a paradox for a declining species (Hamer and Mahony 2007). Large clutch size should confer resilience to environmental factors that might cause population fluctuations, but loss of habitat coupled with the appearance of exotic fish and disease may have over-ridden this.

At the local scale, the extent of a distribution appears of critical importance to population persistence. A feature of the coastal sites where the Green and Golden Bell Frog has persisted is that there are multiple waterbodies located within a relatively small distance (i.e. 1-2 km) (e.g. Broughton Island and Crescent Head, G. Pyke pers. comm.; Homebush Bay, Darcovich and O'Meara 2008; Kooragang Island, Hamer *et al.* 2002a, 2008; Meroo National Park, Daly *et al.* 2008a; Port Kembla, Goldingay and Lewis 1999; Queanbeyan, Osborne *et al.* 2008). It appears likely that this has allowed a larger local population to persist than if only a single waterbody was available. Furthermore, the local population would have occurred as a metapopulation (subpopulations connected by dispersal). This feature now appears to be a key to conserving populations of the species.

Thus, it appears that the ultimate cause of the decline of the bell frogs has been habitat loss and habitat fragmentation which disrupted population processes. The genetic study of Burns *et al.* (2007) revealed that no major dispersal barriers occurred historically across the range of the Green and Golden Bell Frog. Currently, gene flow among fragmented populations is likely to be extremely limited (Burns *et al.* 2004, 2007). With reduced population size at the local scale the species has become vulnerable to the proximate causes of its decline such as fish predation and chytrid infections. The remedy to this is large local population size dispersed across multiple breeding sites.

Conservation Planning

The draft recovery plan for the Green and Golden Bell Frog (DEC 2005) provides a detailed account of the actions that are needed to secure the long-term recovery of this species. The actions listed are by necessity general so their greatest value is by stating how they should be integrated with legislation and other regulations. Here, I want to comment briefly on what progress has been made in recovery during the last 12 years.

In 1996, I argued the case that the conservation plan for this species needed to consider a range-wide approach that would ensure conserving multiple viable populations for each of several geographic areas across the entire range

(Goldingay 1996). Within a given area, it was likely that conservation would require large areas of interconnected sites (White and Pyke 1996). Indeed, Gillespie (1996) noted that the species occupied a mosaic of relatively intact wetlands in East Gippsland, Victoria. Guidelines were provided for habitat restoration based on statistical analysis of breeding and non-breeding sites (Pyke and White 1996). A number of site-based management issues were identified (Daly 1996; Osbourne and McElhinney 1996), including concern about the value of translocation of the species (Greer 1996). It was argued that an experimental approach was needed to identify the causes of bell frog decline (Goldingay 1996; Mahony 1996).

Since 1996, progress has been very slow. The draft recovery plan (DEC 2005) has not been finalised though many actions have been implemented. This recovery plan has advocated range-wide conservation, targeting multiple populations per geographic region throughout the range. An important element of this plan was a recommendation for monitoring of key regional populations (ca. 35 are listed). Monitoring is central to understanding how populations are tracking and may be the basis for site-based recovery actions. To date, it appears that little of this has occurred though there have been some opportunistic surveys conducted and collation of community records for some key populations (see DEC 2007a,b,c,d,e,f,g).

A short-coming of the recovery plan is that there is no focus on evaluating the level of threat to the various key populations. This would enable the identification of specific populations that are in need of urgent attention. Hopefully, this would lead to a targeted approach to recovery actions. At present the approach is ad hoc, with populations receiving attention based on unspecified criteria.

Understanding the population ecology of this species is central to its conservation but our current level of understanding is incomplete. Much more research on this topic is needed. It appears that gambusia (and possibly native fish) will continue to limit population recovery and that management at all sites must address this. O'Meara and Darcovich (2008) describe a program of intensive management of gambusia at Sydney Olympic Park that appears to have had success, but this approach will not be suited to many locations due to expense. However, less costly approaches involving shallow ponds (ephemeral or manufactured) could also be adopted. Many populations would benefit from provision of supplementary breeding sites. Many projects have occurred where breeding habitat has been created (Goldingay and Lewis 1999; O'Meara and Darcovich 2008; Pyke *et al.* 2008; White and Pyke 2008a,b) but documenting how bell frogs respond to such habitat is at a preliminary stage.

Some may view the use of translocation of the Green and Golden Bell Frog as a waste of management resources, particularly in light of the limited success that has been documented. However, the studies conducted thus far (Daly *et al.* 2008b; Pyke *et al.* 2008; Stockwell *et al.* 2008; White and Pyke 2008b) have relied heavily on in-kind contributions that would have been largely unavailable for other recovery actions. Of particular relevance is

that these studies can be viewed as small-scale field experiments. Translocations have had partial success but much has been learnt in the process. In the case of Long Reef, further insight to the impact of fish on bell frog tadpoles has been demonstrated and the influence of pond temperature on tadpole development identified as a management issue. There needs to be recognition that translocation is not a simple management action and that further research is needed to refine how it is conducted.

Conclusion

The Green and Golden Bell Frog suffered a dramatic reduction in range and abundance between 1970 and 1990 (White and Pyke 1996) and population losses have continued during the last 10 years (White and Pyke 2008a). This is symptomatic of a species that remains caught in an extinction vortex (*sensu* Gilpin and Soule 1986). Do we have enough information to reverse this situation? I believe that we do but there needs to be a strong commitment from government agencies. Sydney Olympic Park is an example where such a commitment has been made and results appear encouraging (Darcovich and O'Meara 2008; Muir 2008; O'Meara and Darcovich 2008). One might argue that a vast amount of money has been spent to achieve this but this need not be the case at other locations. The success of the management at Sydney Olympic Park has derived from starting with an appropriate set of conservation principles, which essentially were to retain and enhance the core breeding area and create new areas of breeding habitat away from the core area. This has been achieved and subsequently a commitment has been made to manage the impact of gambusia.

Conservation principles have been articulated for other locations such as Port Kembla (e.g. Goldingay and Lewis 1999). Indeed, the value of creating new breeding habitat

was demonstrated here with breeding occurring in a small constructed pond used by at least 40 adult bell frogs over a 3-year period (Goldingay and Lewis 1999; Goldingay and Newell 2005b). However, continued discussion of what management actions are needed at Port Kembla (e.g. DEC 2007a; Gaia Research 2008) has allowed an immense period of time to be lost. This has coincided with an apparent decline in bell frog abundance and deterioration in the conservation prospects of the local population. At Port Kembla there are many members of the local community extremely willing to assist bell frog conservation (Goldingay 2008). Time will tell whether a real commitment to long-term bell frog conservation materializes from government agencies for this area. The short-term success of one small breeding pond demonstrates that effective management actions need not be very expensive.

There is no doubt that further studies are needed to extend our understanding of how to manage populations of the Green and Golden Bell Frog. Small-scale experimental studies (with adequate controls and replication) should proceed in tandem with other recovery efforts. For example, the influence of the chytrid disease in preventing bell frog population recovery is unknown and must be studied throughout the geographic range of the bell frog. An identified management technique to reduce the impact of chytrid that could be investigated in an experimental context may be as simple as treating small breeding ponds with salt or sea water to prevent chytrid infection (e.g. White 2006). In terms of other recovery efforts, there needs to be recognition that if management reports are not turned into on-ground actions (see White and Pyke 2008a), then significant population losses will occur over the next 10 years. The predicament of the Green and Golden Bell Frog is symptomatic of how threatened the coastal wetlands are in which it occurs. These ecosystems need considerable management attention if they are to retain their biodiversity.

References

Barker, J., Grigg, G. C. and Tyler, M. J., 1995. *A Field Guide to Australian Frogs.* Surrey Beatty & Sons, Chipping Norton.

Beebee, T.J.C. and Griffiths, R.A. 2005. The amphibian decline crisis: a watershed for conservation biology? *Biological Conservation* **125**: 271-285.

Berger, L., Speare, R., Daszak, D., Green, E.D., Cunningham, A.A., Goggin, L. C., Slocombe, R., Ragan, M.A., Hyatt, A., McDonald, K.R., Hines, H.B., Lips, K. R., Marantelli, G. and Parkes, H. 1998. Chytridiomycosis causes amphibian mortality associated with population declines in the rain forests of Australia and Central America. *Proceedings of the National Academy of Science, USA* **95**: 9031-9036.

Berger, L., Speare, R. and Hyatt, A. 1999. Chytrid fungus and amphibian declines: overview, implications and future directions. Pp. 23-33 in *Declines and Disappearances of Australian Frogs*, edited by A. Campbell. Environment Australia, Canberra.

Blaustein, A., Hoffman, P., Hokit, D., Kiesecker, J., Walls, S. and Hays, J. 1994. UV repair and rsistance to solar UV-B in amphibian eggs: a link to population declines? *Proceedings of the National Academy of Science, USA* **91**: 1791–1795.

Burns, E.L., Eldridge, M.D.B. and Houlden, B.A. 2004. Microsatellite variation and population structure in a declining Australian hylid *Litoria aurea*. *Molecular Ecology* **13**: 1745-1757.

Burns, E.L., Eldridge, M.D.B., Crayn, D.M. and Houlden, B.A. 2007. Low phylogenetic structure in a wide spread endangered Australian frog *Litoria aurea* (Anura: Hylidae). *Conservation Genetics* **10**: 17-32.

Caughley, G. and Gunn, A. 1995. *Conservation Biology in Theory and Practice*. Blackwell Science, Melbourne.

Chafer, C. J. 1997. *Biodiversity of Wetlands in the Illawarra Catchments: an inventory*. Illawarra Catchment Management Committee, Wollongong.

Christy, M.T. 1996. The efficacy of using Passive Integrated Transponder (PIT) tags without anaesthetic in free-living frogs. *Australian Zoologist* **30**: 139-42.

Christy, M.T. 2001. The ecology and conservation biology of the green and golden bell frog *Litoria aurea* (Lesson 1829) (Anura: Hylidae). PhD thesis, University of Sydney.

Christy, M. T. and Dickman, C.R. 2002. Effects of salinity on tadpoles of the Green and Golden Bell Frog (*Litoria aurea*). *Amphibian-Reptilia* **23**:1-11.

Clancy, G.P. 1996. The Green and Golden Bell Frog *Litoria aurea* in the Station Creek area of Yuraygir National Park. *Australian Zoologist* **30**: 214-17.

Colgan, D. 1996. Electrophorectic variation in the Green and Golden Bell Frog *Litoria aurea*. *Australian Zoologist* **30**: 170-76.

Courtice, G.P. and Grigg, G.C. 1975. A taxonomic revision of the *Litoria aurea* complex (Anura: Hylidae) in south-eastern Australia. *Australian Zoologist* **18**: 149-163.

Daly, G. 1996. Some problems in the management of the Green and Golden Bell Frog *Litoria aurea* (Anura: Hylidae) at Coomonderry Swamp on the south coast of New South Wales. *Australian Zoologist* **30**: 233-36.

Daly, G. and Senior, C. 2003. Surveys for and habitat assessment of the Green and Golden Bell Frog *Litoria aurea* on the far south coast of New South Wales. *Herpetofauna* **33**: 86-102.

Daly, G., Craven, P. and Hyatt, A. 2008a. Surveys for the Green and Golden Bell Frog *Litoria aurea* at Meroo National Park on the south coast of New South Wales. *Australian Zoologist* **34**: 303-313.

Daly, G., Johnson, P., Malolakis, G., Hyatt, A. and Pietsch, R. 2008b. Reintroduction of the Green and Golden Bell Frog *Litoria aurea* to Pambula on the south coast of New South Wales. *Australian Zoologist* **34**: 261-270.

Darcovich, K. and O'Meara, J. 2008. An Olympic legacy: Green and Golden Bell Frog conservation at Sydney Olympic Park 1993-2006. *Australian Zoologist* **34**: 236-348.

DEC (Department of Environment and Conservation) 2005. Green and Golden Bell Frog *Litoria aurea* (Lesson 1829): Draft Recovery Plan. Department of Environment and Conservation NSW, Hurstville.

DEC (Department of Environment and Conservation) 2007a. *Management Plan for the Green and Golden Bell Frog Key Population at Port Kembla.* Department of Environment and Conservation (NSW), Sydney.

DEC (Department of Environment and Conservation) 2007b. *Management Plan for the Green and Golden Bell Frog Key Population at Coomonderry Swamp.* Department of Environment and Conservation (NSW), Sydney.

DEC (Department of Environment and Conservation) 2007c. *Management Plan for the Green and Golden Bell Frog Key Population within the Crookhaven River floodplain.* Department of Environment and Conservation (NSW), Sydney.

DEC (Department of Environment and Conservation) 2007d. *Management Plan for the Green and Golden Bell Frog Key Population at Sussex Inlet – Swan Lake.* Department of Environment and Conservation (NSW), Sydney.

DEC (Department of Environment and Conservation) 2007e. *Management Plan for the Green and Golden Bell Frog Key Population in the Lower Hunter.* Department of Environment and Conservation (NSW), Sydney.

DEC (Department of Environment and Conservation) 2007f. *Management Plan for the Green and Golden Bell Frog Key Population in the Middle Hunter.* Department of Environment and Conservation (NSW), Sydney.

DEC (Department of Environment and Conservation) 2007g. *Management Plan for the Green and Golden Bell Frog Key Population in the Upper Hunter.* Department of Environment and Conservation (NSW), Sydney.

Gaia Research 2008. *Assessment of habitat, dispersal, corridors and management actions to conserve the Port Kembla Key Population of Green and Golden Bell Frog.* Department of Environment and Climate Change (NSW), Sydney.

Gaston, K.J., Blackburn, T.M., Greenwood, J.J.D., Gregory, R.D., Quinn, R.M. and Lawton, J.H. 2000. Abundance-occupancy relationships. *Journal of Applied Ecology* **37**: 39-59.

Gillespie, G.R. 1996. Distribution, habitat and conservation status of the Green and Golden Bell Frog *Litoria aurea* (Anura: Hylidae) in Victoria. *Australian Zoologist* **30**: 199-207.

Gilpin, M.E. and Soule, M.E. 1986. Minimum viable populations: processes of species extinction. Pp.18-34 in *Conservation Biology: the Science of Scarcity and Diversity*, edited by M.E. Soule. Sinauer Associates, Sunderland, MA.

Goldingay, R.L. 1996. The Green and Golden Bell Frog (*Litoria aurea*) - from riches to ruins: conservation of a formerly common species. *Australian Zoologist* **30**: 248-56.

Goldingay, R.L. 2008. Can the community contribute to conservation of the endangered Green and Golden Bell Frog at Port Kembla? *Australian Zoologist* **34**: 387-392.

Goldingay, R. and Lewis, B. 1999. Development of a conservation strategy for the Green and Golden Bell Frog in the Illawarra Region of NSW. *Australian Zoologist* **31**: 376-87.

Goldingay, R.L. and Newell, D.A. 2005a. Aspects of the population ecology of the Green and Golden Bell Frog at the northern end of its range. *Australian Zoologist* **33**: 49-59.

Goldingay, R.L. and Newell, D.A. 2005b. Population estimation of the Green and Golden Bell Frog at Port Kembla. *Australian Zoologist* **33**: 210-16.

Goodrick, G. N. 1970. *A Survey of Wetlands of Coastal New South Wales.* CSIRO: Canberra.

Greer, A.E. 1996. Why Green and Golden Bell Frogs *Litoria aurea* should not be translocated – a personal opinion. *Australian Zoologist* **30**: 257-58.

Greer, A.E. and Byrne, M. 1995. Sex ratio and frequency of osteological abnormalities in the Australian hylid frog *Litoria aurea* from two apparently unpolluted localities in Sydney, New South Wales. *Australian Zoologist* **30**: 43-48.

Hamer, A.J. and Mahony, M.J. 2007. Life history of an endangered amphibian challenges the declining species paradigm. *Australian Journal of Zoology* **55**: 79–88.

Hamer, A.J., Lane, S.J. and Mahony, M.J. 2002a. Management of freshwater wetlands for the endangered Green and Golden Bell Frog (*Litoria aurea*): roles of habitat determinants and space. *Biological Conservation* **106**: 413-424.

Hamer, A.J., Lane, S.J. and Mahony, M.J. 2002b. The role of introduced mosquitofish (*Gambusia holbrooki*) in excluding the native Green and Golden Bell Frog (*Lito ria aurea*) from original habitats in south-eastern Australia. *Oecologia* **132**: 445–452

Hamer, A.J., Lane, S.J. and Mahony, M.J. 2003. Retreat site selection during winter in the Green and Golden Bell Frog, *Litoria aurea* Lesson. *Journal of Herpetology* **37**: 541–545.

Hamer, A.J., Lane, S.J. and Mahony, M.J. 2008. Movement patterns of adult Green and Golden Bell Frogs *Litoria aurea* and the implications for conservation management. *Journal of Herpetology* **42**: 397–407.

Hamer, A.J., Makings, J.A., Lane, S.J. and Mahony, M.J. 2004. Amphibian decline and fertilizers used on agricultural land in south-eastern Australia. *Agriculture, Ecosystems and Environment* 102: 299-305.

Hero, J-M., Williams, S.E. and Magnusson, W.E. 2005. Ecological traits of decliningamphibians in upland areas of eastern Australia. *Journal of Zoology, London* 267: 221-232.

Humphries, R.B. 1979. Dynamics of a breeding frog community. PhD thesis, Australian National University, Canberra.

Kriger, K.M. and Hero, J-M. 2006. Survivorship in wild frogs infected with chytridiomycosis. *EcoHealth* 3: 171-177.

Laurance, W.F., McDonald, K.R. and Speare, R. 1996. Epidemic disease and the catastrophic decline of Australian rain forest frogs. *Conservation Biology* 10: 406-13.

Lemckert, F. 1996. Surveys for the Green and Golden Bell Frog *Litoria aurea* by the State Forests of New South Wales. *Australian Zoologist* 30: 208-13.

Lewis, B. and Goldingay, R. 1999. Preliminary assessment of the status of the Green and Golden Bell Frog in north-eastern New South Wales. Pp. 94-98 in *Declines and Disappearances of Australian Frogs*, edited by A. Campbell. Environment Australia, Canberra.

Lewis, B.D. and Goldingay, R.L. 2005. Population monitoring of the vulnerable wallum sedge frog (*Litoria olongburensis*) in north-eastern New South Wales. *Australian Journal of Zoology* 53: 185-94.

Mahony, M. 1996. The decline of the Green and Golden Bell Frog *Litoria aurea* viewed in the context of declines and disappearances of other Australian frogs. *Australian Zoologist* 30: 237-47.

Mahony, M. 1999. Review of the declines and disappearances within the bell frog species group (*Litoria aurea* species group) in Australia. Pp. 81-93 in *Declines and Disappearances of Australian Frogs*, edited by A. Campbell. Environment Australia, Canberra.

McFadden, M., Duffy, S., Harlow, P., Hobcroft, D., Webb, C. and Ward-Fear, G. 2008. A review of the Green and Golden Bell Frog *Litoria aurea* breeding program at Taronga Zoo. *Australian Zoologist* 34: 291-298.

Miehs, A. and Pyke, G.H. 2001. Observations of the foraging behaviour of adult Green and Golden Bell Frogs (*Litoria aurea*). *Herpetofauna* 31: 94-96.

Morgan, L.A. and Buttemer, W.A. 1996. Predation by the non-native fish *Gambusia holbrooki* on small *Litoria aurea* and *L. dentata* tadpoles. *Australian Zoologist* 30: 143-49.

Muir, G. 2008. Design of a movement corridor for the Green and Golden Bell Frog *Litoria aurea* at Sydney Olympic Park. *Australian Zoologist*

Murray, B.R. and Hose, G.C. 2005. Life-history and ecological correlates of decline and extinction in the endemic Australian frog fauna. *Austral Ecology* 30: 564-571.

Murray, B.R., Fonseca, C.R. and Westoby, M. 1998. The macroecology of Australian frogs. *Journal of Animal Ecology* 67: 567-579.

NPWS (National Parks & Wildlife Service) 2003. Predation by *Gambusia holbrooki* – the Plague Minnow. Approved Threat Abatement Plan. NPWS, Hurstville, NSW.

O'Meara, J. and Darcovich, K. 2008. Gambusia control through the manipulation of water levels in Narawang Wetland, Sydney Olympic Park 2003-2005. *Australian Zoologist*

Osborne, W.S. and McElhinney, N.A. 1996. Status, habitat and preliminary observations on calling of the Green and Golden Bell Frog *Litoria aurea* on Bowen Island, Jervis Bay National Park. *Australian Zoologist* 30: 218-23.

Osborne, W.S., Littlejohn, M.J. and Thomson, S.A. 1996. Former distribution and apparent disappearance of the *Litoria aurea* complex from the Southern Tablelands of New South Wales and the Australian Capital Territory. *Australian Zoologist* 30: 190-198.

Osborne, W.S., Patmore, S., Hunter, D. and Pietsch, R. 2008. Preliminary observations on a highly-restricted tableland population of Green and Golden Bell frogs on the Upper Molonglo River, NSW. *Australian Zoologist* 34: 271-284.

Penman, T.D. and Lemckert, F.L. 2008. Monitoring the Green and Golden Bell Frog: current problems and an alternative approach. *Australian Zoologist* 34: 373-378.

Penman, T.D., Muir, G.W., Magarey, E.R. and Burns, E.J. 2008. Impact of a chytrid-related mortality event on a population of the Green and Golden Bell Frog *Litoria aurea*. *Australian Zoologist* 34: 314-318.

Primack, R.B. 1998. *Essentials of Conservation Biology*. Second edition. Sinauer, Massachusetts.

Pyke, G.H. 2002. A review of the biology of the Southern Bell Frog *Litoria raniformis* (Anura: Hylidae). *Australian Zoologist* 32: 32-48.

Pyke, G.H. and Miehs, A. 2001. Predation by water skinks (*Eulamprus quoyii*) on tadpoles and metamorphs of the Green and Golden Bell Frog (*Litoria aurea*). *Herpetofauna* 31: 99-101.

Pyke, G H. and Osborne, W.S. (eds) 1996. The Green and Golden Bell Frog *Litoria aurea*: Biology and Conservation. *Australian Zoologist* 30: 132-258.

Pyke, G.H. and White, A.W. 1996. Habitat requirements for the Green and Golden Bell Frog *Litoria aurea* (Anura: Hylidae). *Australian Zoologist* 30: 224-32.

Pyke, G.H. and White, A.W. 1999. Dynamics of co-occurring frog species in three ponds utilized by the endangered Green and Golden Bell Frog *Litoria aurea*. *Australian Zoologist* 31: 12-31.

Pyke, G.H. and White, A.W. 2000. Factors influencing predation on eggs and tadpoles of the endangered Green and Golden Bell Frog *Litoria aurea* by the introduced plague minnow *Gambusia holbrooki*. *Australian Zoologist* 31: 12-31.

Pyke, G.H. and White, A.W. 2001. A review of the biology of the Green and Golden Bell Frog *Litoria aurea*. *Australian Zoologist* 31: 563-598.

Pyke, G.H., White, A.W, Bishop, P.J. and Waldman, B. 2002. Habitat-use by the Green and Golden Bell Frog *Litoria aurea* in Australia and New Zealand. *Australian Zoologist* 32: 12-31.

Pyke, G.H., Rowley, J., Shoulder, J. and White, A. 2008. Attempted introduction of the endangered Green and Golden Bell Frog to Long Reef Golf Course: a step towards recovery? *Australian Zoologist* 34: 361-372.

Retallick, R.W.R., McCallum, H. and Speare, R. 2004. Endemic infection of the amphibian chytrid fungus in a frog community post-decline. *PLoS Biology* 2: 1-7.

Stockwell, M.P, Clulow, S., Clulow, J. and Mahony, M. 2008. The impact of the amphibian chytrid fungus *Batrachochytrium dendrobatidis* on a Green and Golden Bell Frog *Litoria aurea* reintroduction program at the Hunter Wetlands Centre Australia in the Hunter Region of NSW. *Australian Zoologist* 34: 379-386.

Thomson, S.A., Littlejohn, M.J., Robinson, W.A. and Osborne, W.S. 1996. Taxonomy of the *Litoria aurea* complex: re-evaluation of the Southern Tableland populations of the Australian Capital Territory and New South Wales. *Australian Zoologist* 30: 158-169.

Threlfall, C.G., Jolley, D. F., Evershed, N., Goldingay, R.L. and Buttemer, W.A 2008. Do Green and Golden Bell Frogs *Litoria aurea* occupy habitats with fungicidal properties? *Australian Zoologist* **34:** 350-360.

van de Mortel, T.F. and Buttemer, W.A. 1996. Are *Litoria aurea* eggs more sensitive to ultraviolet-B radiation than eggs of sympatric *L. peronii* or *L. dentata? Australian Zoologist* **30:** 150–157.

van de Mortel, T.F. and Buttemer, W.A. 1998. Avoidance of ultraviolet-B radiation in frogs and tadpoles of the species *Litoria aurea, L. dentata* and *L. peronii. Proceedings of the Linnaean Society of NSW* **119:** 173-79.

van de Mortel, T.F., Buttemer, W.A., Hoffman, P., Hays, J. and Blaustein, A. 1998. A comparison of photolyase activity in three Australian tree frogs. *Oecologia* **115:** 366-369.

van de Mortel, T. and Goldingay, R., 1998. Population assessment of the endangered Green and Golden Bell Frog at Port Kembla, New South Wales. *Australian Zoologist* **31:** 48-54.

Wassens, S. and Mullins, B. J. D. 2001. Rediscovery of a Green and Golden Bell Frog population in the Southern Tablelands. *Herpetofauna* **31:** 58-63.

White, A.W. 2006. A trial using salt to protect Green and Golden Bell Frogs from chytrid infection. *Herpetofauna* **36:** 93-96.

White, A.W. and Pyke, G. H. 1996. Distribution and conservation status of the Green and Golden Bell Frog *Litoria aurea* in New South Wales. *Australian Zoologist* **30:** 177-89.

White, A.W. and Pyke, G.H. 1999. Past distribution of the bell frogs *Litoria aurea* and *Litoria castanea* in the Bathurst-Orange district of New South Wales. *Herpetofauna* **29:** 1-9.

White, A.W. and Pyke, G.H. 2002. Captive frog egg numbers – a misleading indicator of breeding potential. *Herpetofauna* **32:** 102-109.

White, A. and Pyke, G.H. 2008a. Green and Golden Bell Frogs in New South Wales: current status and future prospects. *Australian Zoologist* **34:** 319-333.

White, A. W. and Pyke, G.H. 2008b. Frogs on the hop: translocations of Green and Golden Bell Frogs *Litoria aurea in* Greater Sydney. *Australian Zoologist* **34:** 249-260.